

FUNDAMENTALS OF THE PD PROBE MEASURING TECHNIQUE

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Abstract

The presented paper deals with some fundamentals of the non-conventional PD probe measuring technique, which was especially developed for on-site PD diagnosis tests. From the starting point of the classical procedure for decoupling of PD pulses, the peculiarities of the electromagnetic field coupling, using inductive and capacitive sensors, are discussed.

1. Introduction

The measurement of partial discharges (PD) is an essential part of the quality test of electrical equipment since many years [1; 2]. In recent time the PD-tests have grown to be not only an important tool to the manufacturer but also to the user in order to recognize dangerous PD faults on-site when the equipment is put into operation as well as after maintenance. In this respect it seems to be useful to carry out also cyclic PD level monitoring, especially for high worthy equipment.

The use of PD measurements on-site according to the standards is connected to considerable problems.

On one hand requires the connection of the coupling capacitor an interruption of the operating voltage, which may cause economical lost. On the other hand the standardized PD measurement is connected to an increased expenditure in apparatus and handling.

Therefore, an alternative solution is demanded, where the interruption of the operating voltage should be avoided and which should be easy to handle. Concerning this it shows promising to detect PD events based on the non-conventional field coupling mode. So the usually required coupling capacitor is not necessary, i.e. the

diagnosis test can be carried out under service condition. Ideas on this procedure were already presented by KOSKE [3] in the thirtieth. His proposal was even though soon forgotten, much because of the lack of knowledge on PD in this time as well as a still existing economically unacceptable expenditure-to-use ratio.

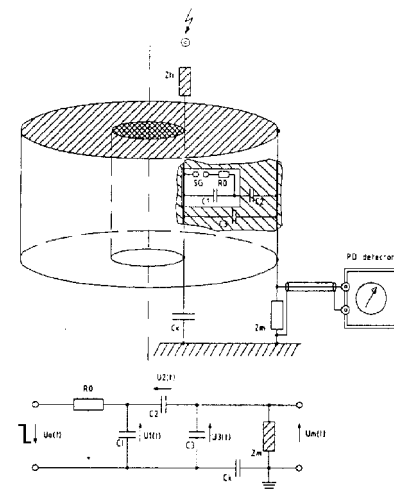


Figure 1: Equivalent circuit for conventional PD detection based on the standard coupling mode using the coupling capacitor C_K and the measuring impedance M_1

Due to the wide laboratory experience of PD measurements nowadays there is not any doubt concerning the usefulness of PD diagnosis tests, not only in laboratory but even on-site. Additionally, the available equipment for field tests is meanwhile significantly improved. In this context the independence of net and therefore the increased flexibility in use as well as the improved signal-to-noise ratio have to be mentioned.

The goal of this paper is, beginning with some fundamentals of the classical PD measuring technique, to mediate the peculiarities of the non-conventional PD probe measuring technique.

2. Conventional PD detection using the coupling capacitor

PD phenomena which occur in dielectric materials of electrical equipment cause electromagnetic transients ranging from about 100 kHz up to 10 MHz, in SF₆-switchgears even up to 1000 MHz.

Therefore, in the standard PD measuring circuit coupling units are usual, which are characterized by a high-pass filter performance. In general the coupling unit consists of the coupling capacitor and the measuring impedance.

In principle the from the PD source radiated electromagnetical field can also be detected by means of antennas. For better understanding this non-conventional coupling mode first some fundamentals of the classical PD detection using a coupling capacitor will be presented.

The by a PD ignition caused transient state can be explained in an easy way, if a simplified equivalent PD circuit is assumed, first developed by GEMANT and PHILIPPOFF [7]. According to a practical example, in the following a segment of a power cable according to Fig.1 shall be considered.

The charge transfer at the location of the PD fault, symbolized by the capacitor C_1 , occurs in the nanosecond range. This process can be approximated by an exponentially decreasing function. According to practical experience the characteristic decay-time-constant should be assumed to $T_1 = 10$ ns, i.e. the transient process is finished after approximately $3 * T_1 = 30$ ns. To imitate this decay-time-constant an assumed spark resistance R_3 shall be introduced, so that the following relation can be written:

$$T_1 = C_1 * R_0 \quad (01)$$

In practice the simplified relations

$$C_2 \ll C_3; C_2 \ll C_1 \quad (02)$$

are almost fulfilled, which makes the estimation below significant easier. Especially the estimation of the detectable PD signal can be done by comparison between the decay-time constant T_1 and the test circuit time-constant T_M . Here T_M is given by

$$T_M = C_3 * Z_M \quad (03)$$

With respect to simplified consideration if is assumed that the capacitance C_K of the coupling capacitor is considerable higher than the total capacitance C_3 of the test object.

Under the condition

$$T_M \gg T_1 \quad (04)$$

a voltage jump U_3 occurs across the terminals of the test object, represented by the capacity C_3 , which is proportional to the apparent charge:

$$Q_3 = U_3 * C_3 = U_1 * C_2 \quad (05)$$

$$Q_3 = Q_1 * C_2 / C_1 \quad (06)$$

Using the already introduced value for the pulse decay-time-constant, which is assumed as $T_1 = 10$ ns, then the condition for a quasi-integration of the PD pulses is sufficiently satisfied for a time-constant $T_M = 10 * T_1 = 100$ ns, representing the response of the test circuit. If a measuring impedance is assumed, which corresponds to the characteristic impedance of a 50 Ohm measuring cable, then at least a test object capacitance of 2 nF would realize the previous given measuring circuit time-constant of 100 ns. Under these circumstances an apparent charge of 100 pC would cause a voltage jump of $U_3 = 20$ mV. This value is reached after a setting time of about $3 * T_1 = 30$ ns.

If the test capacitance is decreased further, i.e. below 2 nF, then also the measuring circuit time-constant T_M is reduced below 100 ns. Finally the measuring circuit shows not longer an integrating behavior, but a high-pass filter characteristic. In this case not the magnitude of the voltage jump but the voltage-time-area, which is delectable at the terminals of the test object and shows the time-depending signal $u_3(t)$, can be considered as a measure of the apparent charge Q_3 . In this case the peak voltage across the test object terminals is

given by the simple equation:

$$U_3 = Q_3 * Z_M / T_1 \quad (07)$$

If again the previous introduced parameters $Q_3 = 100 \text{ pC}$, $Z_M = 50 \text{ Ohm}$ and $T_1 = 10 \text{ ns}$ are assumed, then a peak voltage of $U_3 = 500 \text{ V}$ occurs. The transient process is again finished after a time of about $3 * T_1 = 30 \text{ ns}$, which corresponds to the setting time of the charge transfer in the PD source.

In order to eliminate the influence of the test capacitance C_3 on the detectable pulse charge, PD measuring instruments are recommended having an quasi-integrating performance. It means that the pulse rise time of such equipment should obtain a multiple of the decay-time-constant T_1 of the origin PD pulse, in order to keep the integration error inside tolerable limits. In practice PD instruments having a characteristic rise time in the μs range are used, which corresponds to an upper limited frequency below 300 kHz .

In this case it should be noticed that usually the amplification as well as the integration of the PD pulses is realized in one unit. It could even though be an advantage to separate the two functions, i.e. first to carry out the wide-band amplification of the PD pulses and after that to integrate them electronically. This processing mode is especially useful with respect to noise reduction [8]. In any case this advantage can only be used effectively if the complete test circuit is designed according to the requirements for wide-band PD detection. Especially the grounding of the test area should be done carefully using metallic foils.

3. Non-conventional PD detection using the field coupling mode

First it should be noticed that in the case of the field coupling mode an optimum signal-to-noise ratio can only be achieved if the frequency response of the receiving antenna (in the following called „sensor“) is in the same order as the frequency spectrum of the origin PD pulse. Corresponding to the assumed pulse decay-time-constant $T_1 = 10 \text{ ns}$ at least an upper limited frequency of about 10 MHz is required. Under this

condition, however, an imitation of the PD test circuit by means of concentrated elements is not longer reliable, which is now going to be considered more in detail.

When the geometrical length L_g of the test object is in the order of the electrical length L_e , which represents the transient state, arises always a non-stationary transient state characterized by the generation of traveling waves. The electrical length L_e is given by both, the propagation velocity v_w of the traveling wave and the decay-time-constant T_1 of the PD pulse:

$$L_e = v_w * T_1 \quad (08)$$

For PE-insulated power cables a velocity of $v_w = 0.17 \text{ m / ns}$ can be assumed. Then for $T_1 = 10 \text{ ns}$ the equivalent electrical length becomes $L_e = 1,7 \text{ m}$. Therefore a PE-cable of such a geometrical length must already be considered as an “electrical long“ structure.

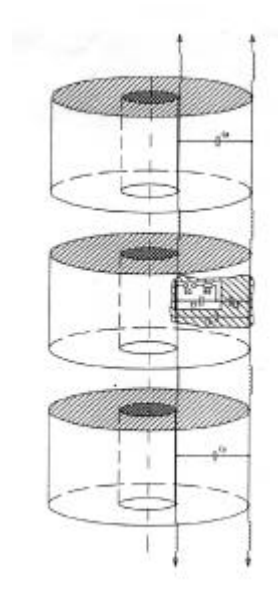


Figure 2: Distributed parameters taking into account the occurrence of traveling waves caused by PD events

In order to imitate the traveling wave guide it is suitable to divide the considered cable into separate parts, as shown in Fig. 2, which results in an equivalent circuit according to Fig. 3. Starting from the PD source two electromagnetic waves propagate in both directions of the cable, so that half the value of the characteristic wave impedance Z_k of the cable acts as an effective impedance. Therefore, in conformity with equ. (07)

the detectable peak voltage is given by:

$$U_3 = 1/2 * Z_K * Q_3 / T_1 \quad (09)$$

For PE-insulated medium voltage cables the characteristic impedance can be approximated by $Z_K = 30 \text{ Ohm}$. For this follows, that for instance an apparent charge of $Q_3 = 100 \text{ pC}$ causes a peak voltage of $U_3 = 150 \text{ mV}$.

In coaxial electrode systems, like PE cables or SF_6 -switchgears, the electromagnetic wave, due to a PD ignition, firstly propagates only inside the insulating dielectric, i.e. between the inner and outer electrode. If SF_6 -switchgears are considered, the electromagnetic transient can easily be detected by means of capacitive sensors, as always done in practice.

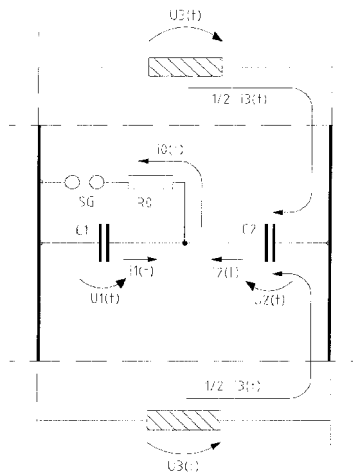


Figure 3: Equivalent PD circuit at non-stationary pulse propagation

So far has it not been very usual to detect PD signals inside the solid insulation of cables, but it could be considered in the future.

Outside of the coaxial system PD events are only detectable, if electromagnetic openings exist, like terminals for power cables (Fig. 4) as well as bushings for transformers and SF_6 -switchgears. The two different field coupling modes, which are applicable, will be considered more in detail in the following.

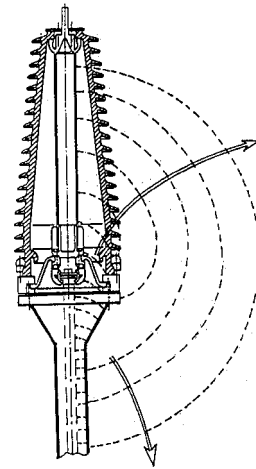


Figure 4: Outflow of PD pulses through a cable terminal

3.1. Inductive field coupling

According to figure 4, the traveling waves propagate first along the inner conductor and then again backwards along the outer conductor of the cable. Therefore, the with the traveling wave connected magnetic field can be detected by means of a coil, i.e. an inductive receiver (L-sensor). For this it should be fixed as close as possible to the outer conductor of the cable, as evident from Fig. 5.

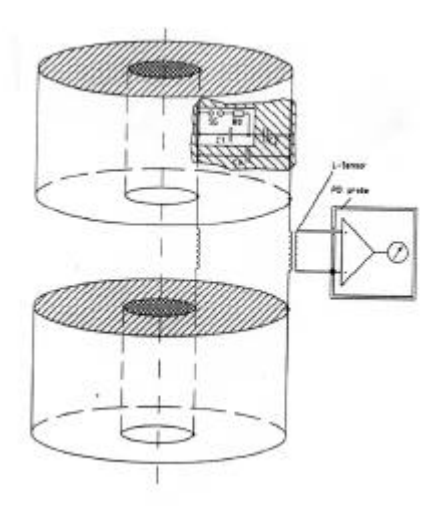


Figure 5: Principle of the inductive field coupling at the outer cable conductor

In order to achieve an optimal signal-to-noise ratio, as much as possible of the transient magnetic field, due to the PD event, should be picked up. This can

be obtained if the L-sensor is placed close to the earth connection lead of the cable termination, as shown by the practical example according to Fig. 6. In this respect it is notable, that L-sensors may react very selectively on each phase.

Overcoupling phenomena between the phases, that could be supposed, due to the common connection to the grounding, has hardly no effect. Therefore, the phase subjected to PD could be distinctly identified, as evident from Fig. 6.

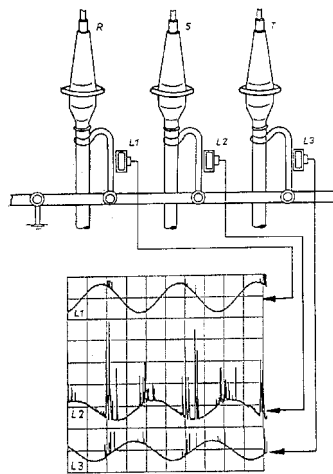


Figure 6: Practical example of inductive field coupling on cable sealing ends

3.2. Capacitive field coupling

Of course, there exists also the alternative to detect not only the magnetic field of PD events but also the electrical field radiated from the test object. For this capacitive couplers (C-sensors) can be used. They may consist of metallic cylinders or discs, as shown in Fig. 7. It should be underlined, that in the case of a power cable only the radiated field outside of the solid insulation can be detected (Fig. 4). It means that it is usually impossible to locate the position of the PD source inside of the dielectric by means of external C-sensors.

There are other conditions, however, if the test object is not well shielded electromagnetically, as in the case of machine bar insulation as well as for resin insulated instrument transformers. As an example Fig. 8 is showing the result of PD fault location in a machine bar insulation.

A further improvement of the location procedure is obtained, if not only the PD level distribution along the test object is recorded, as shown in Fig. 8, but even the PD pulse polarity is indicated, using the differential sensor principle according to Fig. 9. A practical example is evident from Fig. 10.

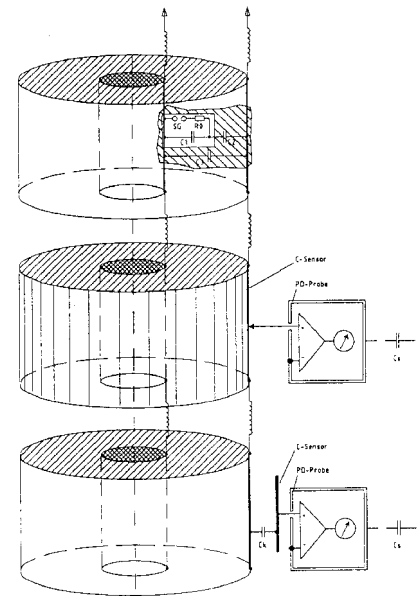


Figure 7: Principle of the capacitive field coupling at the outer conductor of a cable

It is notable that for test objects without outer electromagnetic shielding a very high sensitivity may be obtained. The reason for this is, that the test object capacity, which is symbolized by C_3 in Fig. 1, becomes comparatively low, because it is determined mainly by the capacity between the PD source and the C-sensor. Thereby the detectable voltage jump is raised reciprocally to C_3 , in accordance to equ. (05). Therefore, using C-sensors for PD detection on either machine bar insulation or cable terminals, a measuring sensitivity can be achieved, which is comparable to those of classical PD circuits. It should be mentioned that in this case the equivalent circuit based on concentrated elements (Fig. 1) is again applicable, due to the small geometrical extension in the surroundings of the PD source.

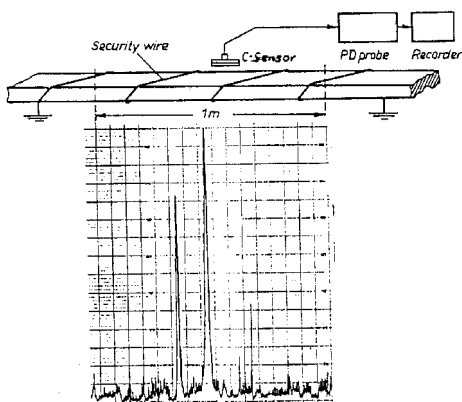


Figure 8: Practical example of PD fault location in a machine bar insulation

4. Peculiarities of the PD probe measurement

In the following some peculiarities will be considered, which have to be taken into account if the non-conventional field coupling mode is used. On one hand the quantitative evaluation of PD events is discussed and on the other hand proposals are presented applicable for calibration of the PD probing.

4.1. Evaluation of the pulse charge

In accordance to the standard PD measurement also the by the non-conventional PD probing detected pulse charge can be regarded as a measure of the space charge, which is generated inside of the PD source. Because neither the attenuation of the PD signal transmitted from the origin PD source to the coupling unit, nor the changing of the time-specific PD pulse parameters are known, only a unknown and strongly reduced part of the origin pulse charge is detectable. In accordance to the standard measurement the by the PD probing detected pulses can be quantified, if a specified calibrating procedure is applied. In order to distinguish the standardized PD quantity „apparent charge“ from the by the PD probing obtained pulse charge, a new PD quantity called „reduced charge“ is introduced.

Due to the fundamental difference between the standard coupling and the field coupling mode it can never be expected, however, that the PD quantity „reduced charge“ corresponds to the

„apparent charge“ even if the same origin PD event is considered.

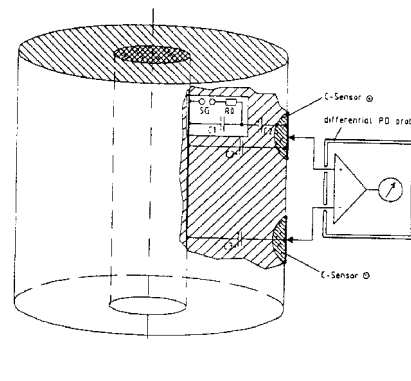


Figure 9: Principle of PD localization by means of the differential probe technique

This fact could be interpreted in such a way, that the non-conventional PD probing may give only qualitative information on PD events and may not allow a quantitative estimation of PD activities. In this context it must be underlined, however, that both measuring procedures are in principle characterized by the same disadvantage in view on the estimation of PD risks. Therefore, the judging of the suitability of the PD probing as a tool for PD diagnostics, other criteria are authoritative, as discussed below.

Due to the well known imperfections of the standard PD measurement, the determination of limits for the „apparent charge“ bases mainly on empirical data [9], which bases on practical experience collected during many years. A physically interpretable correlation to the true charge transfer in the PD source and to the ongoing destruction process in the insulation medium can not be found.

Because PD field measurements up to now has been used in a comparatively small scope, it can not be expected that already well established values exist, which allow a general judgement of the PD failure risk. More experience is still necessary in this subject. Nevertheless, the knowledge so far shows that it seems not to be hopeless to find critical limits for the PD quantity „reduced charge“, which may characterize more or less the PD failure risk of HV equipment in service.

As an example the following table shows a preliminary survey on a classification of PD activities with respect to an evaluation of the PD failure risk, where medium voltage PE-insulated cable sealing ends are considered. The for the „reduced charge“ given ranges base on preliminary experiences. For this the PD probe LDP-5 has been applied in the inductive field coupling mode. It was calibrated according to a procedure as described below under sub-clause 4.2.1.

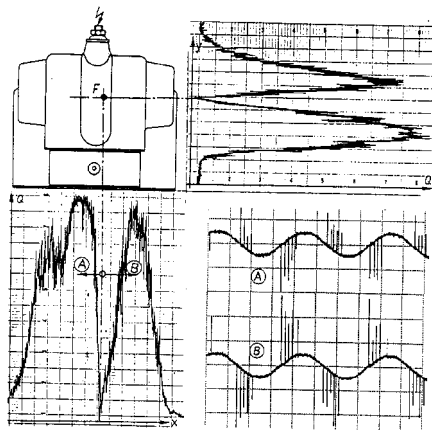


Figure 10: Example of measurement at localization of PD source by means of differential probe at a PE-insulated instrument transformer

<u>class</u>	<u>reduced charge</u>	<u>risk degree</u>
1	$Q_R < 500\text{pC}$	No immediate PD failure risk
2	$500\text{ pC} < Q_R < 5000\text{pC}$	PD failure risk is present, bring to regular supervision, inspections within the scope of planned maintenance
3	$Q > 5000\text{ pC}$	dangerous PD failure, maintenance should be done immediately

It should be noticed that the collection of data concerning critical limits for the PD quantity „apparent charge“ as well as the discussion of those in authorized groups, especially in view of

the standardization, was favorable to all the people involved in it. Opposite to this the collection of data concerning the PD quantity reduced charge is much more complicate. The main reason for this is, that neither the user of HV equipment nor the manufacturer seems to be interested in a public discussion of results obtained in the case of on-site PD diagnosis tests, especially if dangerous PD faults has been identified. This fact makes among other things that user of the PD probe develop their own test philosophies and decide company specific critical limits for the “reduced charge“ which the public has no access to. Thereby is of course the acquisition of useful general empirical values much more difficult.

4.2. Calibration of PD probe measurements

Fundamental it seems close at hand to apply the calibration according to IEC Publication 270 [1] also to the calibration of the PD probing. Preliminary attempts to do this showed, however, that the standardized procedure may causes some non-certainties, due to the peculiarities of the field coupling mode, as explained more in detail in the following.

1. Using the standardized procedure, the calibrating pulse charge is injected into the both terminals of the test object, which simultaneously serve as the decoupling of the PD event. Different to this only one well defined coupling point exists, i.e. in principle a quasi-unipolar decoupling is made. Of course, also the second terminal of the test object takes part in the signal transmission, but it is not well determined and can therefore be regarded as a virtual decoupling pole. Due to this fact, it seems evident to inject the calibrating pulse also quasi-unipolar into the decoupling unit, i.e. into either the L-sensor or the C-sensor.
2. In the case of the standardized PD measurement the „electrical length“ of the test object is mainly determined by the integration characteristics of the total PD measuring circuit, where also the PD detector is included. From this an electrical length, ranging between 10 m and 100 m, can be derived. Usual test objects can therefore be considered as

concentrated, i.e. the through PD pulses triggered transient state can be viewed as quasi-stationary.

In contrary to this usual test objects have to be viewed as „electrical long“, if the non-conventional field coupling mode is applied. In this context it should be noticed, that also the connection lead between the calibrator and the test object may act as „electric long“, if the length exceeds two meters. This is always the case if the dimension of the test object is in the meter range, as for instance for power transformers.

In addition to this also the time parameters of the calibrating pulses may significantly influence the result of calibration of the field coupling mode, whereas in the case of standardized PD measurement it has no significant influence if the specified tolerance limits for the time parameters are held. Hence it can be concluded, that the standardized calibration procedure seems not applicable in the case of the PD probing. Separated by the special nature of field coupling, following two calibration procedures have to be distinguished.

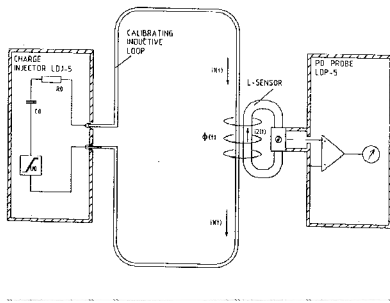


Figure 11: Calibration of the inductive field coupling mode

4.2.1. Inductive field coupling

The point of decoupling, for which mostly the ground connection lead is preferred, can be simulated by an inductive loop, as evident from Fig. 11. Using the calibrator, it is supplied by well defined pulse charges. The rise time of the step pulse generator inside of the calibrator should be much lower than the rise time of the integrator of

the PD probe, say 1/10 of it. Considering the PD probe LDP-5, which is characterized by a rise time at the output "CHARGE" of approximately 300 ns, the duration of the pulse charge injection should not exceed 30 ns. This time corresponds to the rise time of the step pulse generator inside of the calibrator. This requirement is always fulfilled by the Charge Injector LDJ-5, where the origin rise time of the internal step pulse generator is less than 10 ns.

Since it is not a rarity that in the case of on-site diagnostic tests PD pulse magnitudes of a few 1000 pC have to be detected, the Charge Injector LDJ-5 was designed in such a way, that it meets these requirements. It generates calibrating charges up to 10 000 pC, where the internal calibrating capacitor is less than 100 pF.

It should be noticed that the PD quantity „reduced charge“, which refers to the calibrating arrangement according to Fig. 11, guarantees a well reproducible PD probing. This is caused by the similar conditions of the charge injection of the inductive sensor in both cases, i.e. the calibration and the actual PD detection.

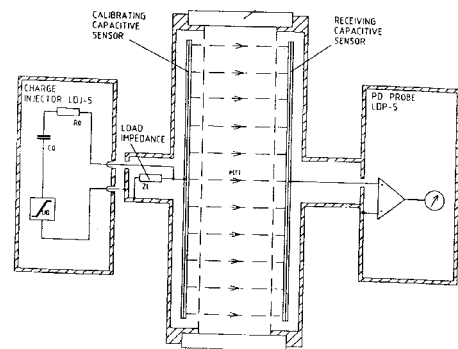


Figure 12: Calibration of the capacitive field coupling mode

4.2.2. Capacitive field coupling

Similar to the inductive field coupling also in the case of the capacitive field coupling mode the PD signal is received quasi-unipolar. Therefore, this coupling mode should also be simulated by an unipolar charge injection.

The arrangement, shown in Fig. 12, appears to be most favorable. As evident from Fig. 12 the output of the calibrator is connected to a plane disc acting as a radiating antenna. The receiving C-sensor is positioned at a fixed distance to it, using a cylindrical insulating spacer. Both, the housing of the calibrator and the PD probe remain potential free. In this way the signal back-circuit takes place using the stray capacitance of the calibrating arrangement. Any additional galvanic connection is avoided in order to eliminate traveling waves which may influence the reproducibility.

It should be noted that the obtained result of calibration has to be viewed as sensor-specific. The result can never be transmitted to other sensor types, especially if the geometrical dimensions are different.

Opposite to the inductive field coupling, the reproducibility of the capacitive field coupling in the case of practical PD probing is more restricted. This is mainly due to the more or less non-defined stray capacities between PD probe and test object, which can also be influenced additionally by the operator. Therefore, this coupling mode should be only preferred, if either a rough evaluation of PD events is sufficient with respect to the judgement of developing trends or in the case of PD location, as previously described.

4.3. Noise influence

Due to physically based difference in the coupling principles it seems impossible to compare the signal-to-noise ratio of both procedures, i.e. the standard method and the PD probing, especially if on-site conditions have to be taken into account. Preliminary experience, however, showed that the inductive field coupling is characterized by a favorable signal-to-noise ratio. Since the field coupling mode offers also more flexibility in comparison to the standardized method, because PD detection can be carried out on equipment under service, i.e. an interruption of the operation voltage can be avoided, the advantages of PD probing on-site are indisputable.

In this context it should be underlined, that it can

not be the goal of on-site PD diagnostics to repeat again the PD quality test, already made within the final test in the HV laboratory by the manufacturer. The main task is rather to recognize dangerous PD faults, which can cause sudden breakdown. Therefore, first of all heavy PD events have to be detected. They are mainly caused by gross defects, due to non-correct installation or repair faults as well as to over voltages and thermal mechanical over stressing.

Such kind of PD faults usually cause an extremely high PD level, ranging from some 1000 pC up to 10 000 pC, sometimes even more. Thus the requirement concerning the desired signal-to-noise ratio is essentially reduced. Nevertheless, it should not be underestimated that the solution of problems of the electromagnetic compatibility is one of the most important task, which has to be solved within the PD probing.

5. Summary

Based on the present knowledge of practical application the PD probing for on-site diagnosis tests the following statements can be drawn:

1. In principle the PD probing can qualitatively be compared with the standardized PD measurement. This is especially the case with respect to the obtained oscilloscopic records. Thus the same computer-aided measuring technique can be used for further data-acquisition.
2. There is also no fundamental difference to the standardized procedure with respect to the judgement of developing trends of PD events.
3. Like the standard technique also the results of PD probing may be applied for the evaluation of the PD failure risk only on the basis of practical experience, from which empirical data are derived. An immediate correlation between the detected PD quantity and the actual charge transfer in the PD source does not exist.
4. In general both, the user and the manufacturer, are not interested in publication

of data, obtained by the PD probing on site, especially if dangerous PD faults have been recognized. This circumstance makes it difficult, to generalize critical values for the PD quantity „reduced charge“.

5. Even if the PD probe measuring technique is used only since a few of years for PD diagnosis tests, there exists already practicable knowledge for individual components of HV equipment in order to classify the degree of PD failure risk.
6. From a physical point of view there exist a fundamental difference concerning the quantitative evaluation of the detected pulse charge. Therefore, in analogy to the standardized quantity „apparent charge“ the „reduced charge“ was introduced in order to quantify the PD probing.
7. In order to calibrate the inductive field coupling mode an inductive loop has to be used as a test imitation, to which the L-sensor is attached as close as possible. In order to calibrate the capacitive field coupling mode it is suitable to use a plane disc like an antenna. Opposite to this the C-sensor is placed at a fixed distance, given by an insulating spacer.
8. The calibrator for PD probing should be designed in such a way, that the transition time for charge injection is less than 30 ns. The internal calibrating capacity should not exceed 100 pF.
9. Since the main goal for on-site PD diagnostics is, to recognize dangerous PD faults in HV equipment with respect to an early warning, and such PD are mainly characterized by charge magnitudes in the range of several thousands of pC, the required signal-to-noise ratio may be in general much lower than in the case of PD quality tests in the laboratory.

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